CURRENT-INDUCED TRANSITIONS IN SUPERCONDUCTING INDIUM FILMS

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THESIS

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ABSTRACT

The correlation between several critical currents defined for the transition between the superconducting and the normal resistive state in thin indium films was determined. Using various pulse techniques, the current required to reach the threshold of resistance $\underline{I}_t$, the dc current which produces a complete transition $\underline{I}_c$, the current which restores half of the resistance in the absence of Joule heating effects $\underline{I}_{50}$, and the pulsed current which "simultaneously" switches the film $\underline{I}_s$, were measured.

$\underline{I}_{50}$ and $\underline{I}_s$ were found to have the same functional temperature dependence, having a constant relationship such that $\underline{I}_s$ is 1.1 times $\underline{I}_{50}$.

$\underline{I}_t$ was measured with good accuracy over the temperature range 1.6° to 3.4°K. $\underline{I}_c$ was measured over the same range and the two currents were compared to observe the effect of Joule heating and the degree to which that effect can be reduced by changing conditions of heat conduction away from the film.

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1. Introduction

Several metals exhibit the phenomena of superconductivity at temperatures below a critical temperature $\underline{T}_c$ associated with each particular metal. Investigations into the nature of the transition from the superconducting state to the normal resistive state in thin metallic films have been underway from some time in an effort to contribute to a complete theory for superconductivity. Such a transition can be induced by placing the film in a large enough magnetic field, by passing a sufficiently large current through the film, or by some combination of field and current.

Consider, for example, a film 5 mm long of rectangular cross-section, 60 microns wide and one micron thick. As dc current is slowly increased from zero through this superconducting film, no voltage appears across the film until a threshold current $\underline{I}_t$ is reached. At this threshold, the film enters an intermediate state wherein the film is broken up into some kind of mixture of resistive and superconducting states. Bremer and Newhouse propose a model which explains certain experimental results for current-induced transitions.[1] As current is increased through the film, a resistive channel soon extends across the film. Within this channel,

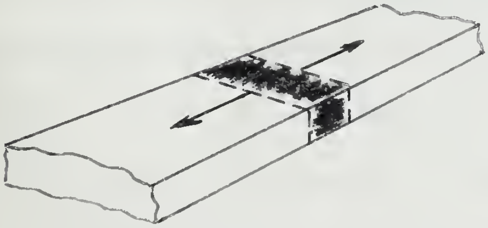

Fig. 1. Resistive channel in superconducting film.

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[1] John W. Bremer and V. L. Newhouse, Phys. Rev. Letters, Vol. 1, 282, 1958

temperature rises due to Joule heating and the boundaries of the channel reach the critical temperature corresponding to the local current density. The channel enlarges. A resistive domain can be expected to form initially where "necking in" of magnetic field lines takes place due to non-uniform current density. As current is increased above $\underline{I}_t$, the equilibrium extent of the resistive domain increases. A value of current is reached for which the domain rapidly sweeps throughout the film. This is called the dc critical current $\underline{I}_c$. Values of current greater than this will produce more than one initial domain of resistivity and result in even faster transitions.

If current is introduced through the film in pulses which are shorter in duration than the time required for Joule heating to enter into the transition, values of current higher than $\underline{I}_c$ will be required to achieve a complete transition; such a transition will be magnetically induced so that all parts of the film are switched simultaneously. This current is the simultaneous switch current $\underline{I}_s$. The relationships between the currents thus far described are shown in Fig. 2, typical of a thin indium film evaporated onto a glass substrate.[2] Threshold current $\underline{I}_t$, is shown as the dashed curve. $\underline{I}_t$ and $\underline{I}_c$ merge (at 3.0°K) because the value of current required to reach the threshold is so high that Joule heating immediately sweeps the resistive domain

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[2] Foundations of Future Electronics, Chapter VI, E. C. Crittenden, Jr., to be published by UCLA and McGraw-Hill

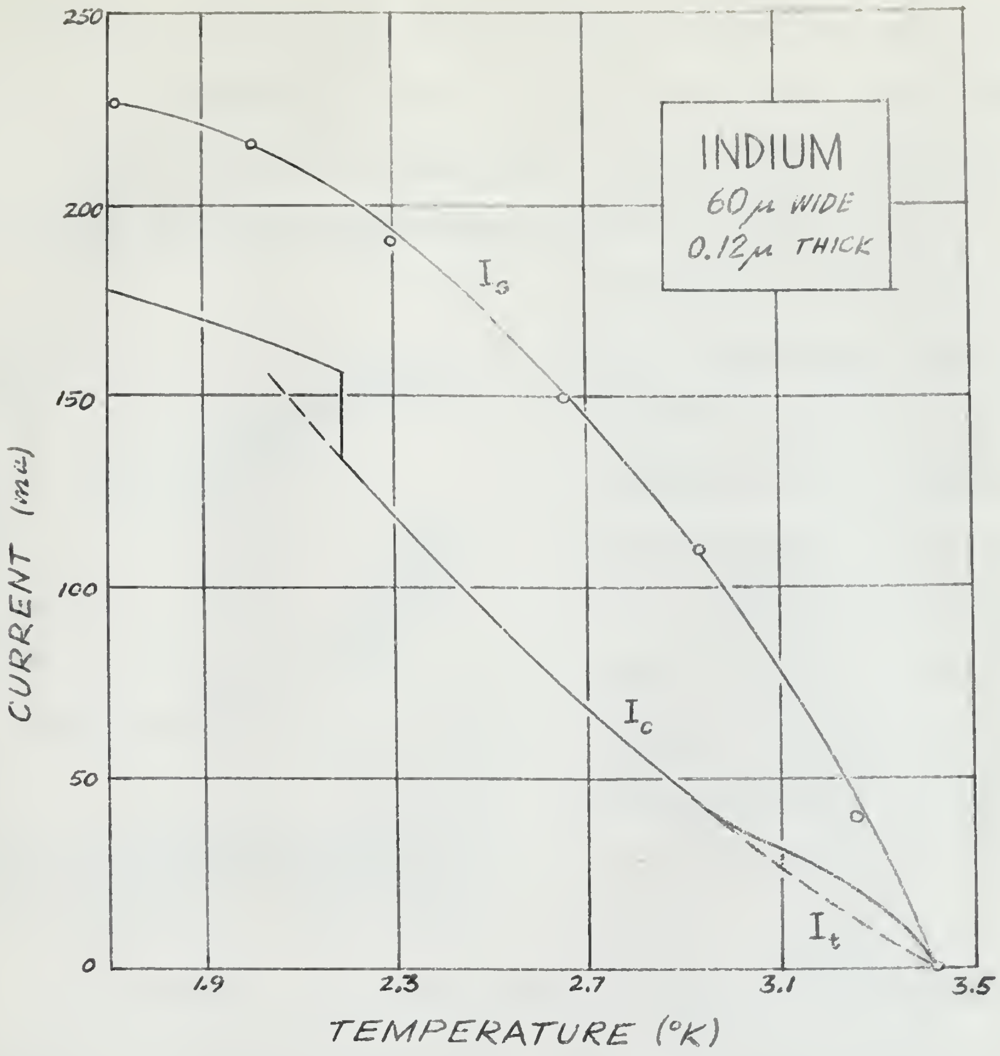

Fig. 2. Critical currents in thin indium film (after E. C. Crittenden, Jr., 1959)

to the ends of the specimen. Then, as the lambda point of helium is reached at 2.186°K, the helium becomes a far superior heat conductor and a distinction can again be made between $\underline{I}_t$ and $\underline{I}_c$. There is no such discontinuity in the curve of $\underline{I}_s$.

Another recent experiment in current-induced transitions employed both fast-pulsing techniques and improved heat

conduction to study the nature of the switch in thin tin films.[3] By applying current pulses of 0.5 μsec rise time and 4 μsec duration, "isothermal" transitions--transitions free from Joule heating effects--were obtained in the range of temperatures just below $\underline{T}_c$. From these data, the current for which the resistance reached half of its maximum value was taken as a criterion for experimental verification of the theory of Ginzburg which relates critical current and critical field in that region.[4]

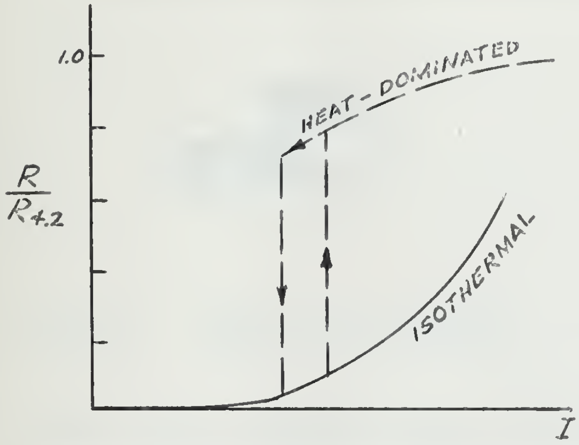

Fig. 3. Isothermal and Joule heat-dominated transition (after Bremer and Newhouse)

An adequate theory for current-induced transitions through the intermediate state does not exist. Data on the transition are essential and a correlation between the several criteria for critical switch currents will be valuable in formulating a complete theory. The present experiment was prompted by these considerations.

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[3] J. W. Bremer and V. L. Newhouse, "On Current Transitions in Superconducting Tin Films", to be published in Phys. Rev.

[4] V. L. Ginzburg, Doklady Acad. Nauk, Vol. 118, p. 464 (1958)

2. Experimental Procedure

a. Specimens

Specimens of indium were prepared at Space Technology Laboratories, Inc. by vacuum deposition of a film onto substrates of optically polished glass or quartz.[5] The geometry was that shown in Fig. 4, where the substrate disc diameter is one inch and its thickness is three millimeters. The broad area of film on either side was designed to reduce contact resistance; indium lugs were included to insure good contact. Dimensions of the individual films appear in the appendix.

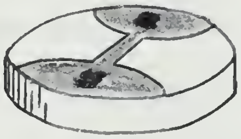

Fig. 4. Specimen geometry

For the experiment specimens were mounted in a holder which incorporated circuitry shown schematically in Fig. 5. Doubling back of two of the leads formed a loop which effectively reduced the spurious pulse caused by the $L\frac{di}{dt}$ response of the film due to its finite self-inductance.

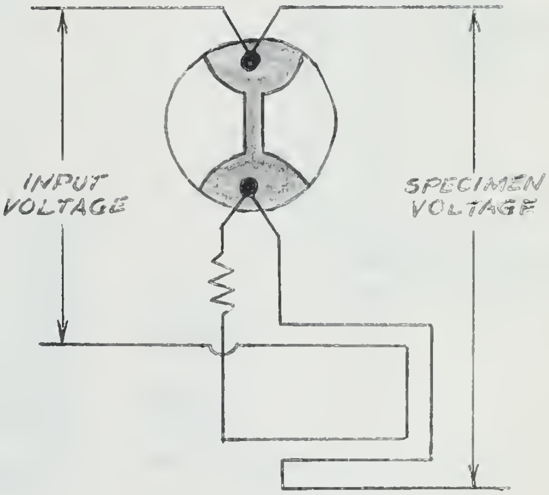

Fig. 5. Schematic specimen wiring diagram.

At temperatures below 4°K crystalline quartz exhibits a

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[5] Process described in The "Persistor", A Superconducting Memory Element, E. C. Crittenden, Jr., John N. Cooper, and F. W. Schmidlin, to be published Proc. IRE, 1960

thermal conductivity about 4×10^3 times that of glass.[6] Thus it was possible to study similar films under markedly different conditions of heat conduction.

b. Cryogenics

Specimens were immersed in a bath of liquid helium, the holder being suspended by its coaxial lead cables. Low temperatures were attained by mechanical pumping on the helium vapor.[7] A regulator designed by E. C. Crittenden, Jr., maintained the vapor pressure with precision at any desired value. The liquid helium bath was contained in a Dewar flask, surrounded by a liquid nitrogen heat shield in a second Dewar flask, as shown below:

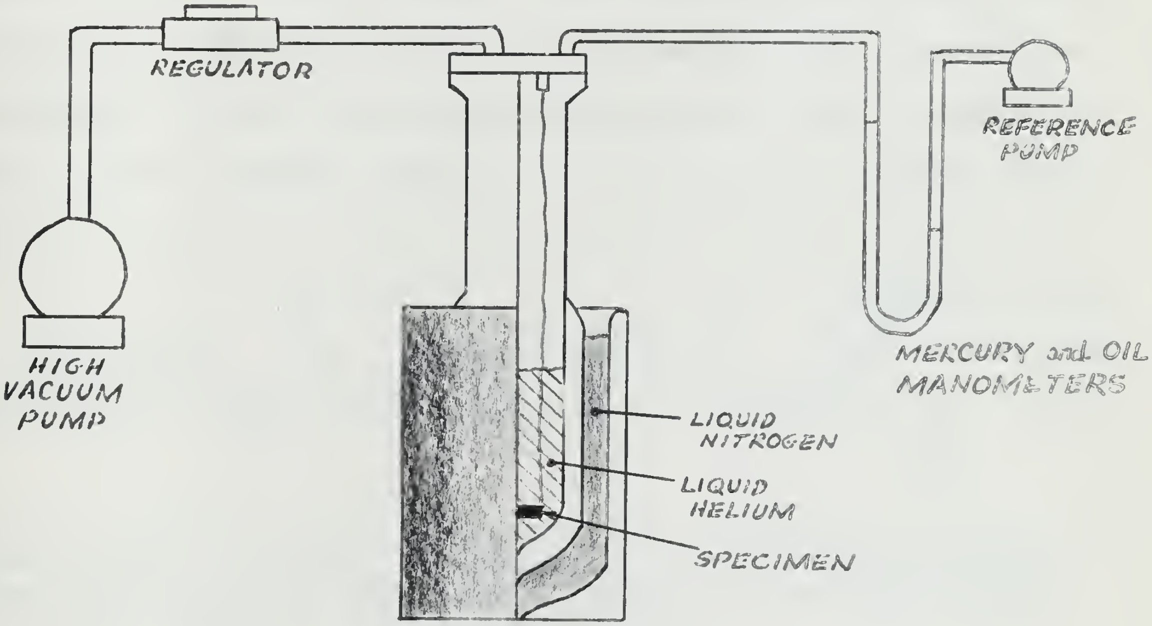


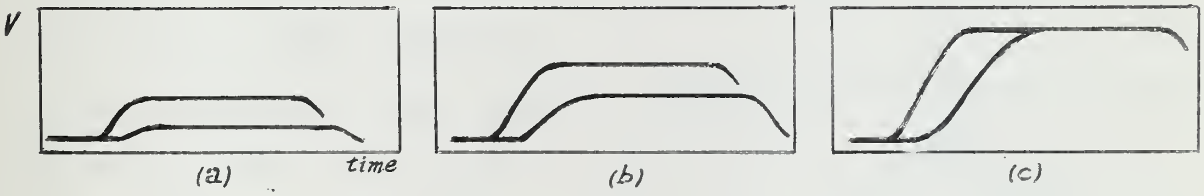
Fig. 6. Schematic diagram of cryogenic equipment

[6] American Institute of Physics Handbook, McGraw-Hill, 1957

[7] Vapor pressure-temperature schedule according to Squire [2]

c. Measurements

Simultaneous switch current data were obtained using square pulses (120 per second) from an SKL Model 503 fast-rise pulse generator (rise time 1 mμsec). These pulses were put through fifty-ohm coaxial cables into the specimen in series with a fifty-ohm resistance. With a Tektronix Type 541 Oscilloscope, and a dual trace preamplifier, the input pulse and specimen response could be superimposed and viewed simultaneously. Vertical sensitivities of the two traces were adjusted so that the two pulse heights coincided after the specimen had been driven completely resistive. Then, as the input pulse height was manually increased from zero, the specimen (lower) trace formed, rose, overtook the input trace just as the switch was complete, and remained in coincidence thereafter. As the switch neared completion, the specimen response trace literally jumped into coincidence with the input trace. At this point, the value of the input pulse was recorded and I_s was calculated from that input voltage and an input impedance of fifty ohms.



(a) (b) (c)

Fig. 7. Voltage vs time for fast pulse. Specimen voltage (lower trace) (a) forms (b) overtakes and (c) becomes coincident with input voltage (upper trace) as the input pulse height was manually increased from zero.

Threshold and dc critical currents were measured using a

current regulating circuit designed by E. C. Crittenden, Jr. This device provided a steadily increasing current through the specimen which drove it to the resistive state, at which point a thyratron fired to open the circuit and prevent possible destruction of the specimen. Data was recorded in the form of oscilloscope photographs showing voltage versus current at each temperature. In addition, I_c was read directly on a milliammeter. Figure 8 is a sketch of a typical oscilloscope photograph. Threshold current I_t is estimated as the point where voltage first increases above the horizontal axis.

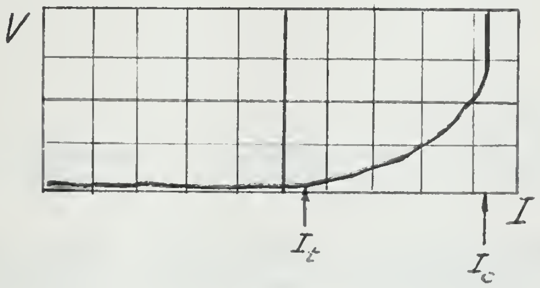


Fig. 8. Superconducting film response to slowly increased dc

A special pulse-shaping, cathode-follower circuit was designed to produce a triangular waveform from the output of a Teletronics Model PG-200 AA pulse generator. This circuit supplied pulses with near-linear leading edges and slightly exponential decay; variables in the circuit made it possible to choose any rise time between 15 mμsec and 20 μsec.

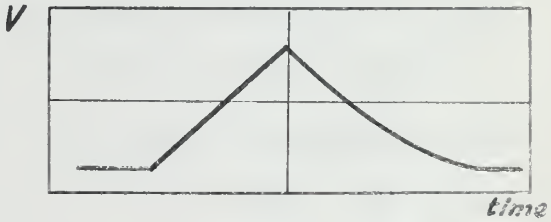


Fig. 9. Triangular input waveform for I_{50}, I_t and I_p determinations

With such a triangular pulse across the specimen in series with fifty ohms resistance, the voltage across the specimen

alone was observed with an oscilloscope. As the input pulse increased from zero, a definite threshold of resistance could be seen, as determined by the first detectable specimen voltage on a 1 mv/cm scale. Increase of input pulse caused specimen pulse to progress in the manner sketched below:

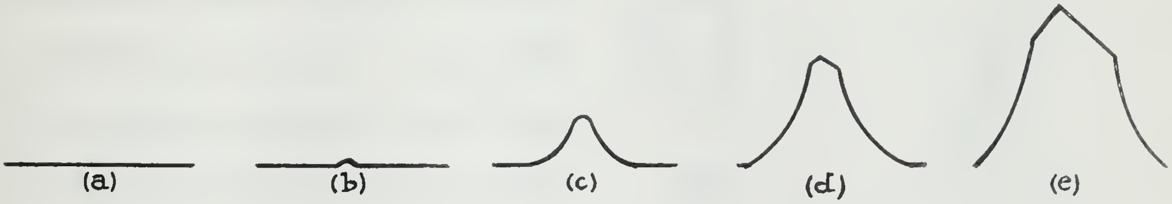


Fig. 10. Development of specimen voltage in response to gradually increased triangular input current pulse.

Figure 10 (a) represents the condition before any resistive region has developed across the film. As current is increased, resistance first appears as indicated in Fig. 10 (b). Further increase in input current causes the specimen voltage to increase with the form shown in (c), the extremum being rounded. At a definite input current, this roundness gave way to distinct cornering, shown in (d), with a slight linear elongation on the trailing edge. The value of current required to produce this form was recorded as the critical switch current. Increasing the input pulse beyond this point resulted in the overdriven form (e). In the region near the peak, the specimen pulse assumed the form of the input pulse. The critical current measured in this manner using a 0.5 μsec rise time was designated the <u>peak current</u> I_p. Similar measurements were made with input pulse rise times of 5, 10, and 15 μsec.

Data on the current required for the restoration of fifty per cent of the normal resistance was obtained with the 0.5 μsec rise time triangular pulse. Specimen voltages corresponding to various input currents were recorded so that resistance could be calculated for various currents and these plotted as fractional resistance versus current at each temperature. The current required to produce fifty per cent of the in-helium resistance, called I_{50}, was taken from these curves.

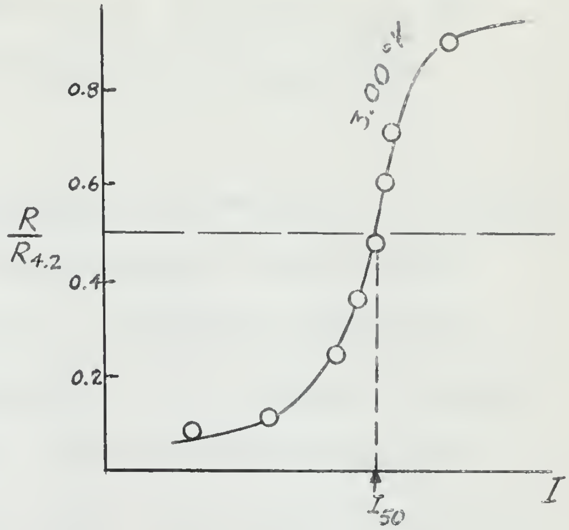


Fig. 11. Fractional resistance curve.

3. Results and Discussion

By applying the pulse techniques described above to a variety of glass- and quartz-backed films, data was obtained for I_t, I_c, and I_s which is consistent with that reported by other experiments using similar measurements.[8] Typical of this work is that shown for specimen G-217 in Fig. 12.

The simultaneous switch current I_s, can be seen to approximate a functional dependence

$$I_s = \gamma I_{so} \left[1 - (T/T_c)^4\right]$$

where I_{so} is the intercept of I_s extrapolated to 0°K, T is

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[8] E. C. Crittenden, Jr. et al, "Critical Currents in Thin Superconducting Thin Films", International Conference on the Structure and Properties of Thin Films, at Bolton Landing, N. Y., 1959

the specimen temperature, and T_c is the film's critical temperature. The squares plotted on Fig. 12 show the fourth power function. Below the lambda point of helium, I_c approaches the same functional dependence on temperature. I_{so} is about 1.35 times I_{co}.

Both the analysis of oscilloscope photographs of slowly increasing direct current and the triangular input pulse methods were used to determine I_t. Agreement between the two methods was excellent: the latter was preferred because it provided a direct measurement over the whole range of temperatures. Continuous values of I_t for temperatures well below the lambda point were measured in this way.

Figures 13, 14, and 15 present the results obtained for three quartz-backed films.

Immediately apparent is the greater spread between I_t and I_c. This can be attributed to the higher thermal conductivity of quartz. It has been noted that the portion of I_c below the lambda point of helium exhibits approximately a fourth power dependence on temperature between I_{co} and zero current at T_c. Quartz backing, since it markedly increases conduction of heat away from the film, permits I_c to more nearly approach fourth power temperature dependence above the lambda point in the vicinity of T_c.

Another criterion, I_p, the value of current required to complete the switch to the resistive state, based on input pulses with rise time 0.5 μsec, is shown superimposed

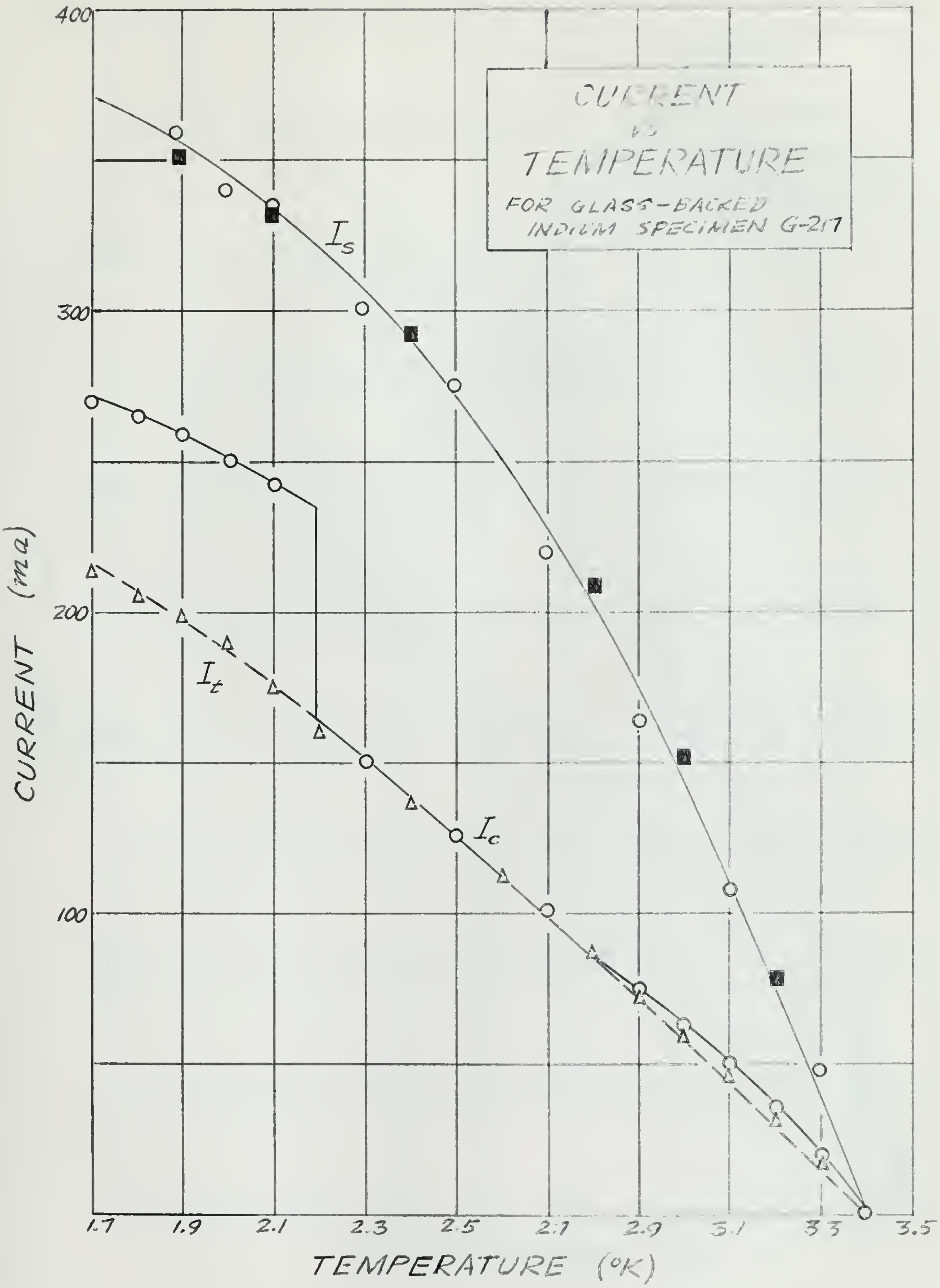
CURRENT
vs
TEMPERATURE
FOR GLASS-BACKED
INDIUM SPECIMEN G-217
I_s
I_c
I_t
400
300
200
100
CURRENT (ma)
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
TEMPERATURE (°K)

Fig. 12

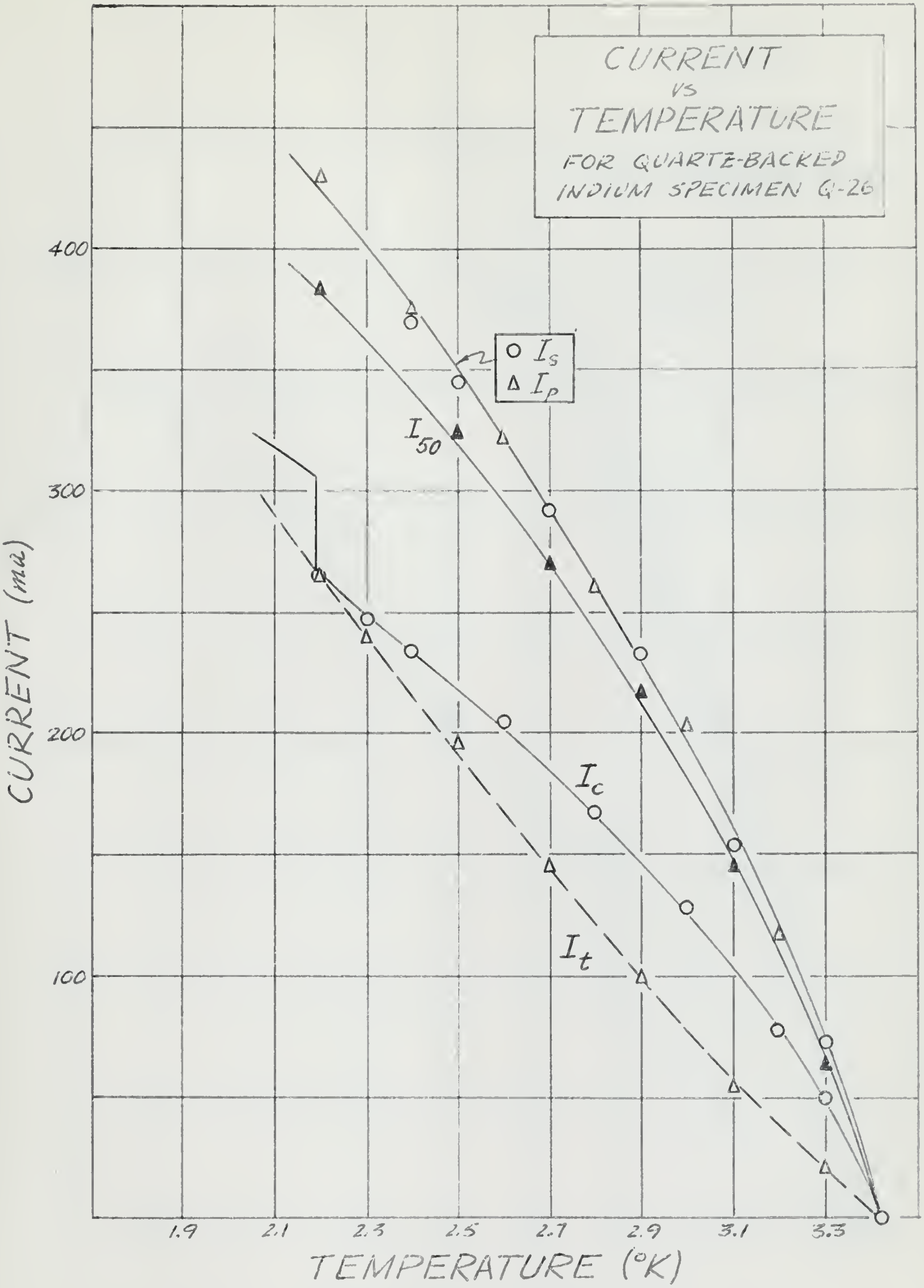
CURRENT
vs
TEMPERATURE
FOR QUARTZ-BACKED
INDIUM SPECIMEN Q-26
○ I_s
Δ I_p
I_{50}
I_c
I_t
CURRENT (ma)
400
300
200
100
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
TEMPERATURE (°K)

Fig. 13

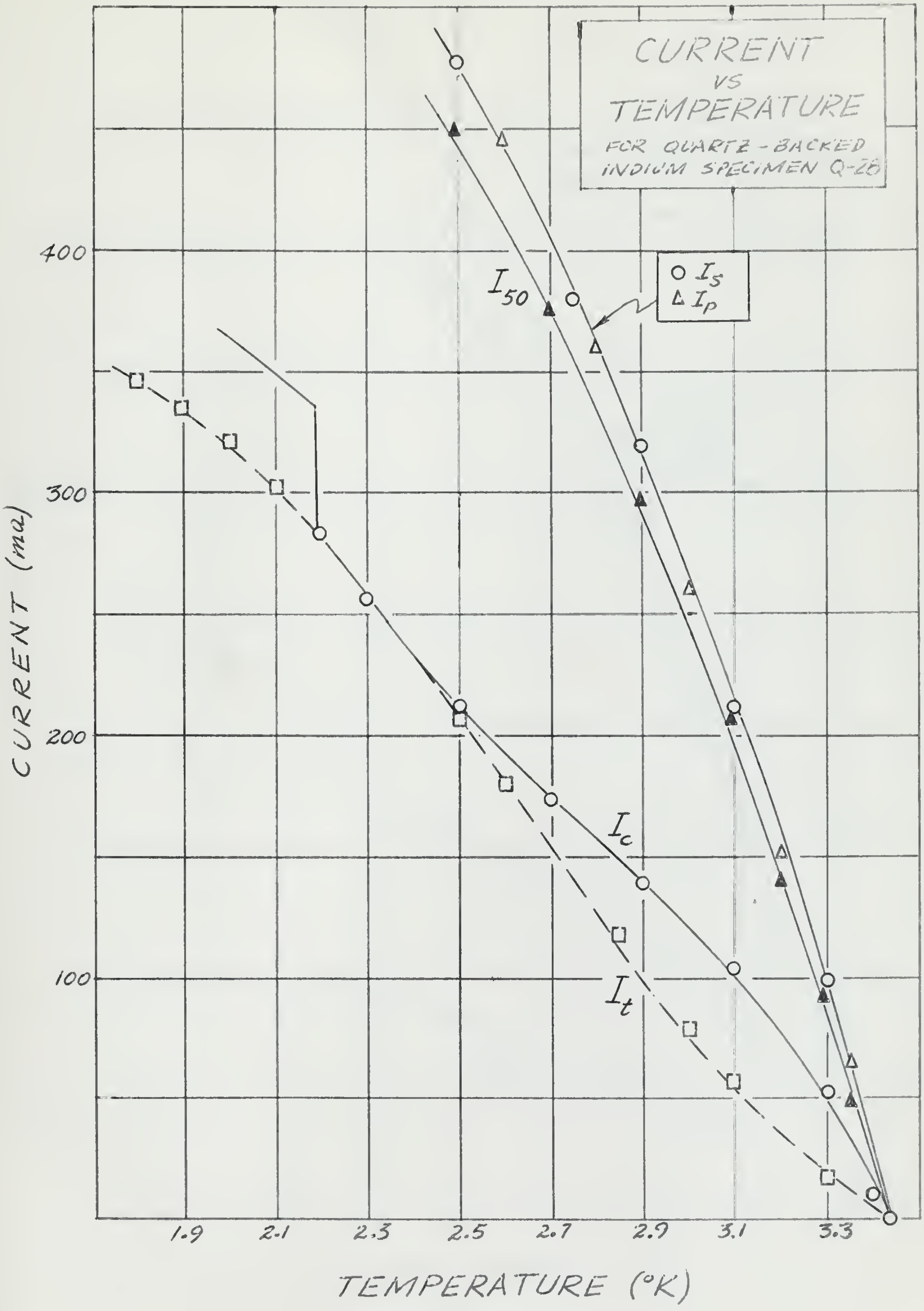
CURRENT
VS
TEMPERATURE
FOR QUARTZ-BACKED
INDIUM SPECIMEN Q-26
○ I_s
△ I_p
I_{50}
I_c
I_t
400
300
200
100
CURRENT (ma)
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
TEMPERATURE (°K)

Fig. 14

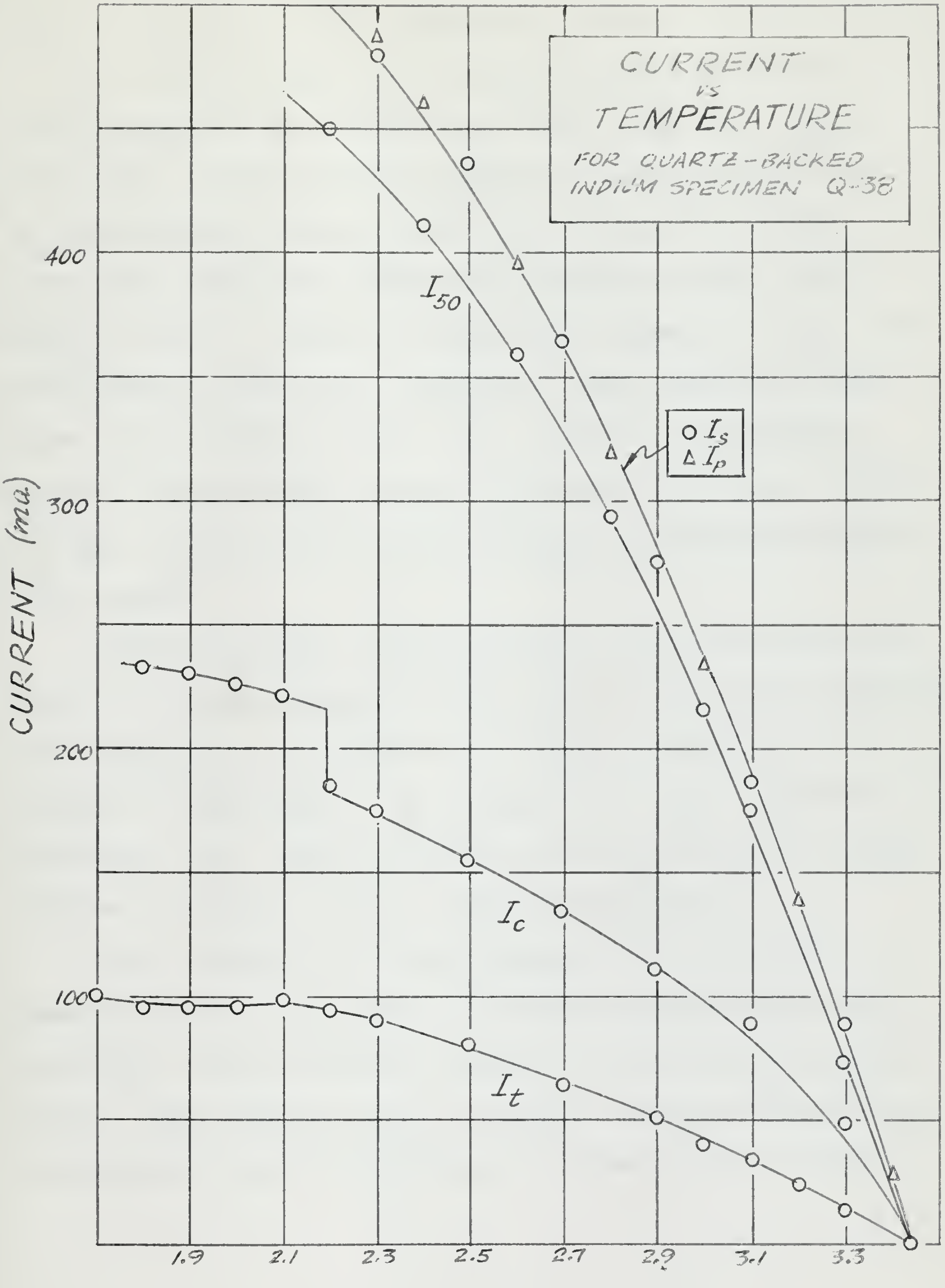
CURRENT
vs
TEMPERATURE
FOR QUARTZ-BACKED
INDIUM SPECIMEN Q-38
○ I_s
△ I_p
I_{50}
I_c
I_t
CURRENT (ma)
400
300
200
100
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
TEMPERATURE (°K)

Fig. 15

on $\underline{I}_s$. These two current curves are the same experimentally.

Also shown is $\underline{I}_{50}$, the current required to restore fifty percent of the normal resistance using the $0.5\,\mu$sec input pulse. This value of current is quite distinct from the simultaneous switch current $\underline{I}_s$. Points for the $\underline{I}_{50}$ curve were taken from fractional resistance curves like those of Fig. 16. Since the $\underline{I}_{50}$ curve appeared to have the same shape as that of $\underline{I}_s$, graphs of I_{50}/I_s against temperature were prepared to test for a constant relationship. Figure 17 shows these curves. It appears that $\underline{I}_{50}$ is about 0.91 $\underline{I}_s$, and that the same functional dependence on temperature exists.

Figure 18 shows a family of curves of the current required to completely restore the resistance in a glass-backed film. Each curve represents a different rise time for the triangular input pulse. $\underline{I}_s$ and $\underline{I}_p$ (rise time, $0.5\,\mu$sec) are coincident. $\underline{I}_c$, the dc criterion, and $\underline{I}_t$ are equal in this temperature region and are shown for reference.

Such a family of currents suggests that $\underline{I}_s$ is approached as the upper limit of current required for rapid switching, and that current pulses with rise times somewhat greater than $0.5\,\mu$sec begin to produce Joule heating effects and therefore achieve switching for lower current values.

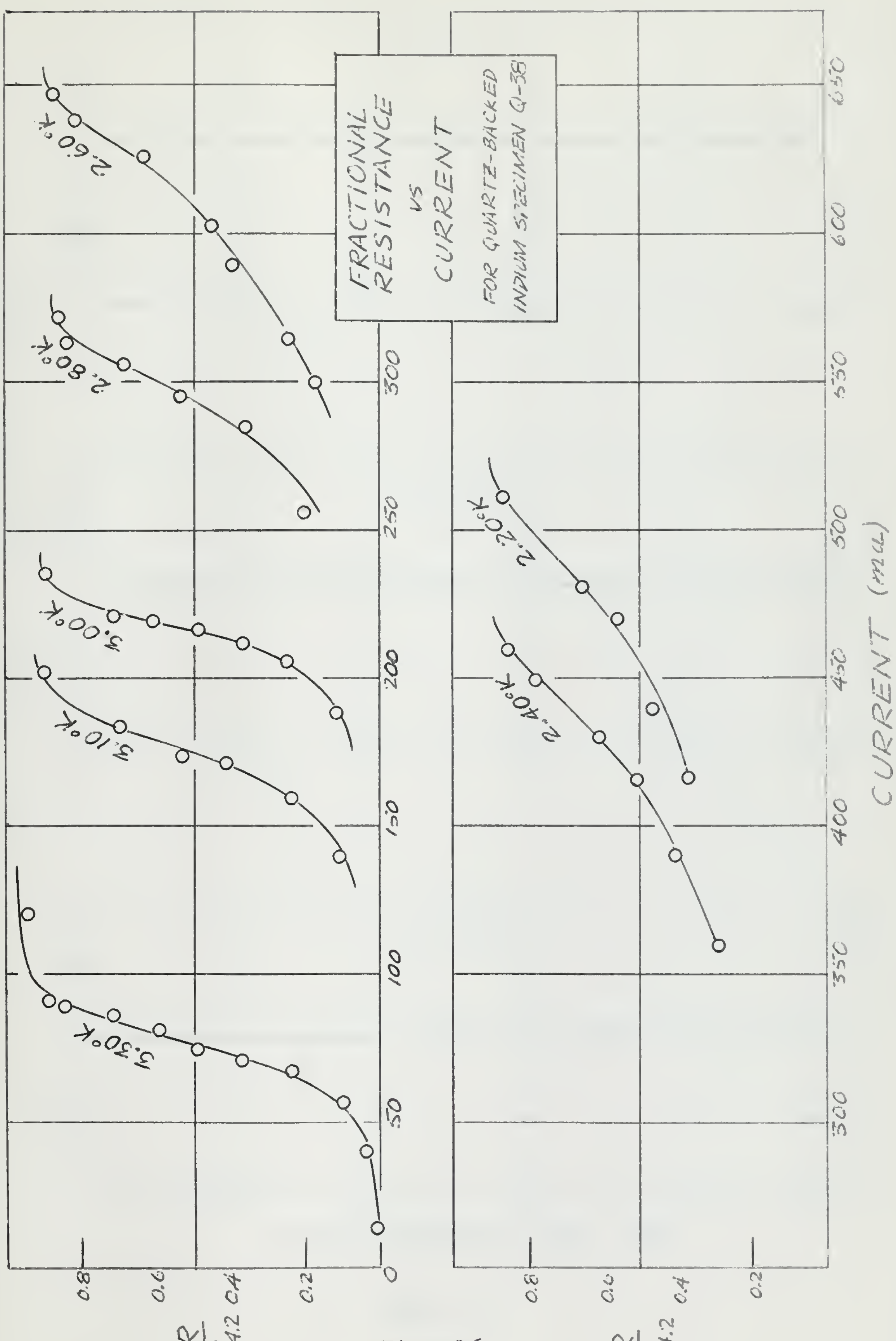
FRACTIONAL
RESISTANCE
vs
CURRENT
FOR QUARTZ-BACKED
INDIUM SPECIMEN Q-38
2.60°K
2.80°K
3.00°K
3.10°K
3.30°K
2.20°K
2.40°K
0
50
100
150
200
250
300
350
400
450
500
550
600
650
0.2
0.4
0.6
0.8
CURRENT (ma)
R/R4.2
R/R4.2

Fig. 16

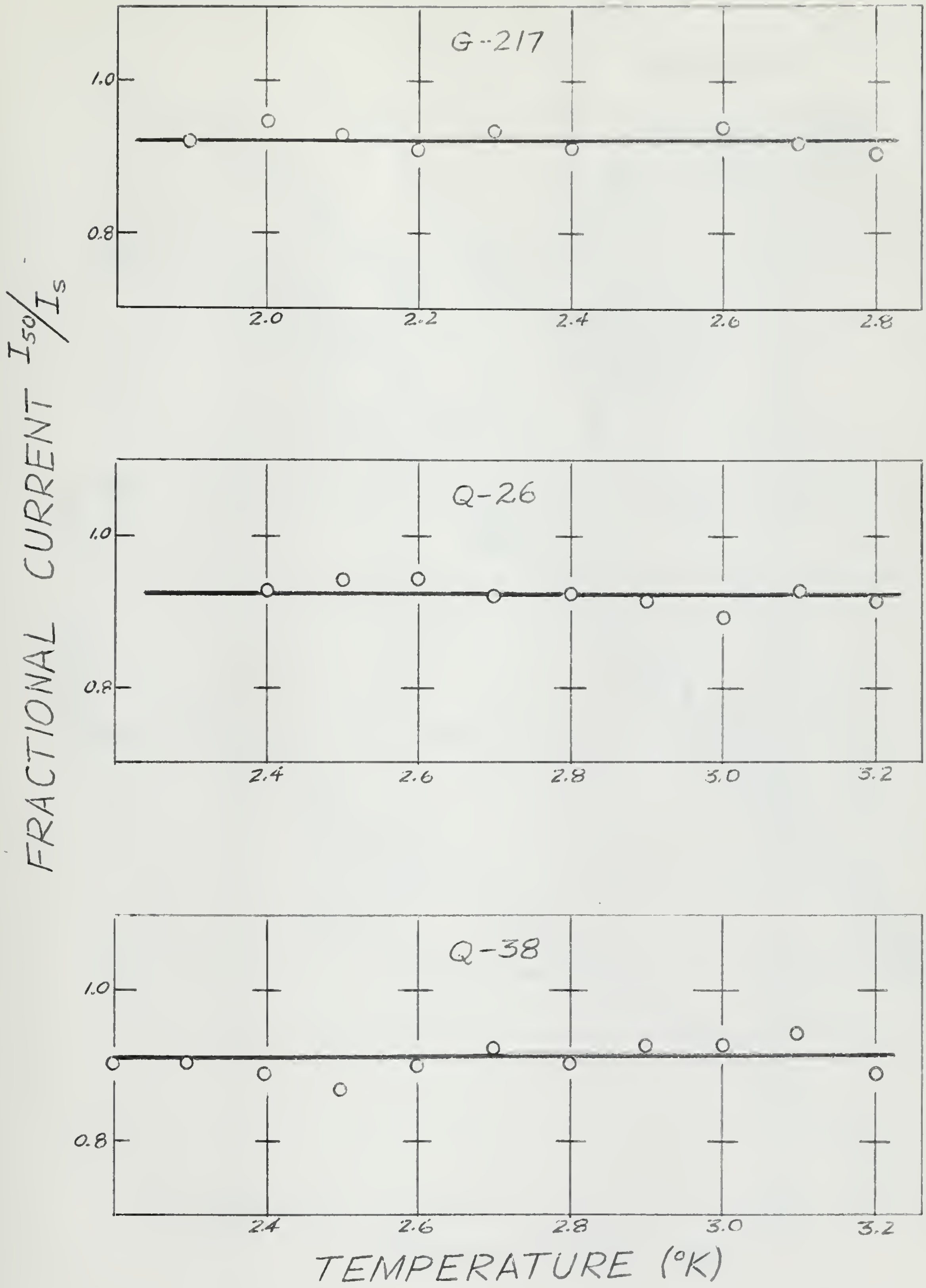
G-217
Q-26
Q-38
1.0
0.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
FRACTIONAL CURRENT I_{50}/I_s
TEMPERATURE (°K)

Fig. 17

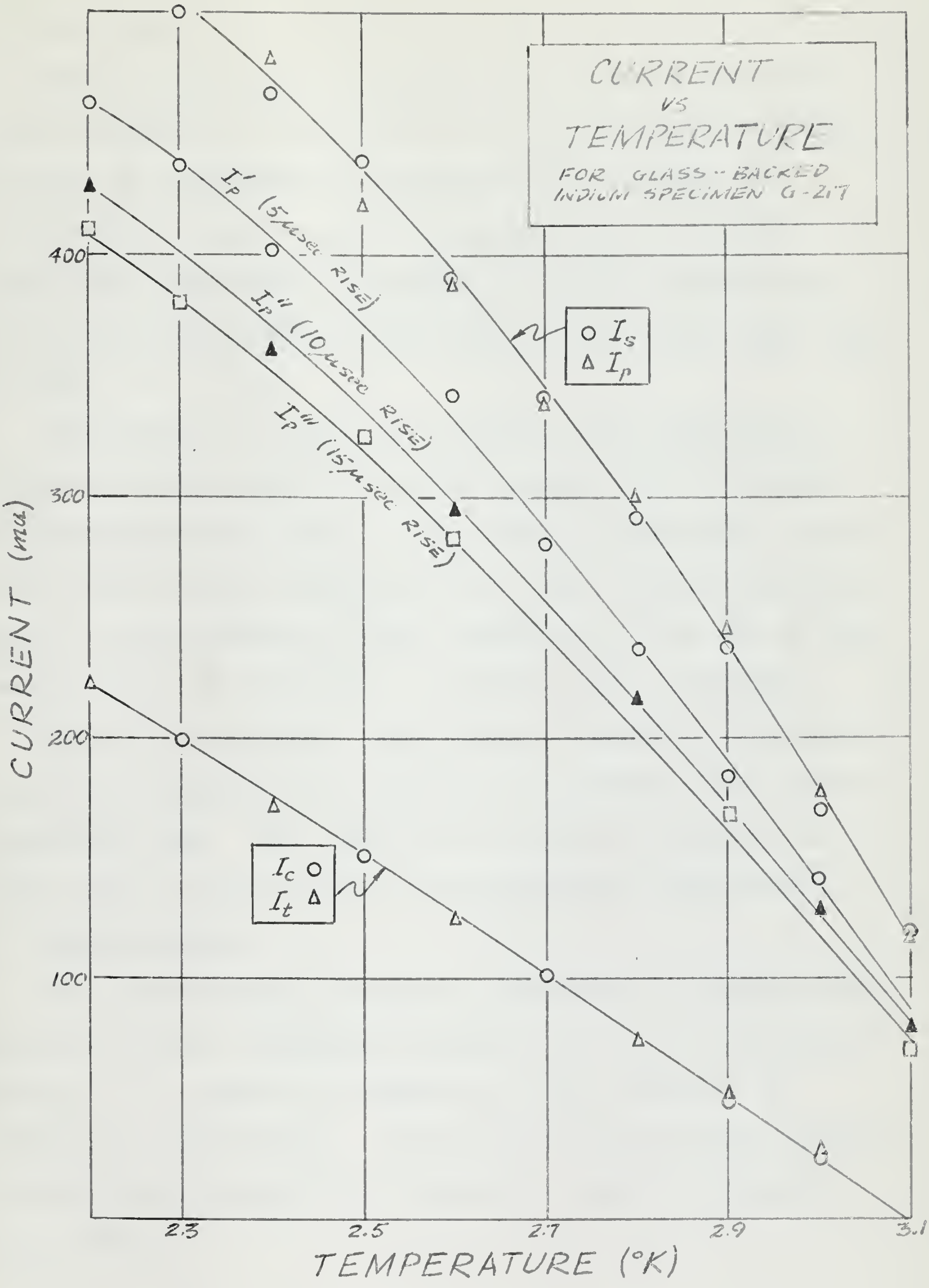
CURRENT vs TEMPERATURE
FOR GLASS-BACKED INDIUM SPECIMEN G-217
○ I_s
△ I_p
I'_p (5μsec RISE)
I''_p (10μsec RISE)
I'''_p (15μsec RISE)
I_c ○
I_t △
400
300
200
100
CURRENT (ma)
2.3
2.5
2.7
2.9
3.1
TEMPERATURE (°K)

Fig. 18

4. Conclusions

Because $\underline{I}_{50}$, $\underline{I}_p$, and $\underline{I}_s$ appear to have the same functional dependence on temperature and the constants relating them can be experimentally determined, it follows that measurement of any one of these currents by appropriate pulse techniques serves to define all of the simultaneous switch characteristics of the film. The ratio $\underline{I}_s : \underline{I}_p : \underline{I}_{50}$ is about 1 : 1 : 1.1.

Furthermore, a family of currents, each associated with a different degree of Joule heating, can be measured by varying the rise time of a triangular input pulse. Further study in this direction should yield interesting information on the progress of Joule heating in films and on the maximum rise time tolerable for simultaneous switching.

Use of a triangular input pulse provides an excellent means for measuring the threshold of resistance in a superconducting film. The method can be used for accurate results over the whole range of liquid helium temperatures.

5. Acknowledgments

The enthusiastic guidance in theoretical considerations and experimental technique offered by Dr. E. C. Crittenden and Dr. J. N. Cooper, as advisers to this project, is gratefully acknowledged. Assistance in electronics and cryogenics problems given by Mr. Kenneth C. Smith is greatly appreciated.

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APPENDIX I

Table of Film Dimensions

Specimen	G-217	Q-26	Q-28	Q-38
Substrate	glass	quartz	quartz	quartz
Mass	60.2 mg	40.0 mg	20.7 mg	20.8 mg
Width	60μ	118μ	250μ	240μ
Length	5.1 mm	5.1 mm	5.1 mm	5.1 mm
Thickness*	0.47μ	0.17μ	0.063μ	0.065μ
Resistance 297°K	16.5 Ω	22.7 Ω	29.4 Ω	29.8 Ω
4.2°K	0.29 Ω	0.67 Ω	1.75 Ω	1.90 Ω
T_c (°K)	3.391	3.425	3.434	3.437

*Specimen thickness was computed by the formula:

$$R = \rho\frac{L}{A} = \rho\frac{L}{sw}$$

, where: R = resistance at room temperature (297°K)

ρ = resistivity of Indium (9.1×10^{-8} ohm meter)

L = film length

A = film cross-sectional area

s = film thickness

w = film width